An Empirical Investigation of Convective Planetary Boundary Layer Evolution and Its Relationship with the Land Surface

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ABSTRACT

Relationships among convective planetary boundary layer (PBL) evolution and land surface properties are explored using data from the Atmospheric Radiation Measurement Program Cloud and Radiation Test Bed in the southern Great Plains. Previous attempts to infer surface fluxes from observations of the PBL have been constrained by difficulties in accurately estimating and parameterizing the conservation equation and have been limited to multiday averages or small samples of daily case studies. Using radiosonde and surface flux data for June, July, and August of 1997, 1999, and 2001, a conservation approach was applied to 132 sets of daily observations. Results highlight the limitations of using this method on daily time scales caused by the diurnal variability and complexity of entrainment. A statistical investigation of the relationship among PBL and both land surface and near-surface properties that are not explicitly included in conservation methods indicates that atmospheric stability in the layer of PBL growth is the most influential variable controlling PBL development. Significant relationships between PBL height and soil moisture, 2-m potential temperature, and 2-m specific humidity are also identified through this analysis, and it is found that 76% of the variance in PBL height can be explained by observations of stability and soil water content. Using this approach, it is also possible to use limited observations of the PBL to estimate soil moisture on daily time scales without the need for detailed land surface parameterizations. In the future, the general framework that is presented may provide a means for robust estimation of near-surface soil moisture and land surface energy balance over regional scales.

1. Introduction

During the course of the day, the effects of the earth's surface radiation and energy balances are felt throughout the lower atmosphere. Turbulence and convection act to transport and mix heat and moisture within a region of the lower troposphere of variable depth known as the planetary boundary layer (PBL). The daytime (or convective) PBL is directly affected by interactions at the land surface and serves as a "short-term memory" of land surface processes on diurnal time scales (Stull 1988). As a result, the time evolution of atmospheric temperature and humidity profiles in the PBL and turbulent fluxes and temperature and moisture conditions at the land surface are dependent upon (and feed back on) one another.

One question yet to be resolved in studies of these interactions is how conditions and fluxes at the land surface can be diagnosed using observations of the PBL and its diurnal evolution. The need for this type of approach has become evident in light of the many challenges involved in measuring PBL energy budgets and modeling land–atmosphere interactions via soil–vegetation–atmosphere transfer schemes. Further, atmospheric forecast models at regional to global scales require accurate representation of surface energy and water budgets, and estimating these processes at scales applicable to such models using point-scale observations or models is a major challenge. A key hypothesis of this work is that by using the well-mixed PBL as an

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integrated diagnostic of land surface conditions and fluxes, it may be possible to estimate regional-scale land surface fluxes without the need for specification of soil and vegetation properties, upscaling procedures, or in situ flux measurements.

Previous efforts to obtain land surface information from PBL observations have relied on in situ measurements of the PBL (Betts and Ball 1994), a combination of PBL and land surface data through conservation principles (Kustas and Brutsaert 1987), and 1D modeling of the PBL (Diak and Stewart 1989; Diak 1990; Diak and Whipple 1993, 1994). Each of these methods is constrained by the general paucity of detailed measurements of the PBL and incomplete treatment of the controls, relationships, and feedbacks between the PBL and the land surface.

With these issues in mind, the objectives of this paper are 1) to improve understanding of the factors controlling convective PBL evolution and 2) to develop methods of estimating surface conditions and fluxes from measurement of PBL evolution, focusing on observable properties of the PBL and the land surface rather than models of complex processes. The emphasis is on *daily* variability in these properties, using the PBL as an integrator of surface conditions at *regional* scales.

2. Background and previous studies

a. Conservation of heat in the PBL

Previous attempts to exploit PBL–land surface relationships have focused on closure of heat, water vapor, and carbon dioxide budgets in the PBL, but there has been little application of conservation principles to a large sample of individual days and little consensus regarding the treatment of some of the components involved (e.g., entrainment and advection), and available methods require many parameterizations, assumptions, and in situ measurements of PBL properties. These issues need to be addressed before daily surface fluxes and properties such as soil water content can be diagnosed operationally from PBL variables.

The conservation of heat in the PBL is represented by

$$\frac{\partial\bar{\theta}}{\partial t} + \frac{\overline{U_j}\partial\bar{\theta}}{\partial x_j} = \frac{\nu_\theta \partial^2\theta}{\partial x_j^2} - \frac{1}{\bar{\rho}C_p}\left(L_v E - \frac{\partial\overline{R_{nj}}}{\partial x_j}\right) - \frac{\partial(\overline{u_j'\theta'})}{\partial x_j}, \tag{1}$$

where θ is potential temperature, t is time, U_j is mean wind speed in the jth direction, ν_θ is molecular thermal diffusivity, C_p is specific heat of moist air, ρ is air density, L_v is latent heat of evaporation, E is flux of latent heat from the surface to the atmosphere, R_{nj} is net radiation in the jth direction, and u_j' and θ' are the turbulent wind and temperature components (Kustas and Brutsaert 1987), respectively, which represent the vertical fluxes of sensible heat.

6. Conclusions

In this paper we examined 132 days of PBL and land surface data from the ARM-SGP site. Results from conservation analyses show that estimation of daily surface fluxes is not possible using traditional or mean approximations for budget terms. Given these limitations, additional variables were examined and empirical methods of describing these relationships were developed. These methods use observations to predict and explain PBL development and structure and are applicable to individual days on regional scales. Perhaps most important is that the methods presented in this paper are based on easily observable variables (stability, soil moisture, PBL height, and 2-m potential temperature change) relative to those necessary for conservation approaches.

A natural and useful extension to the methods described in this paper provides a simple means to estimate soil water content. Daily observations of soil moisture are extremely difficult to obtain directly, and this method does a good job of estimating soil moisture from routinely measured variables. The integrating nature of the PBL with respect to land surface processes, combined with the close relationship between soil moisture and Bowen ratio, suggests that PBL properties should be diagnostic of regional-scale land surface energy balance. It is expected that this method can be applied to locations other than ARM-SGP. It would require a similar analysis to the one presented here to develop the appropriate relationships for the location in question, and research is currently ongoing to investigate the sensitivity of the approaches developed here to varying surface and atmospheric conditions. The results from this work are also particularly useful from a remote sensing perspective because high-resolution observations of PBL structure are now available from sensors on satellite platforms such as the National Aeronautics and Space Administration (NASA) *Terra* [Moderate-Resolution Imaging Spectroradiometer (MODIS)] and *Aqua* (MODIS and Atmospheric Infrared Sounder) spacecraft. Future research efforts will focus on examining relationships over varied land surface conditions and applying this method to remote sensing data.